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10 January 2002

SUBJECT: Authorization for Release of Technical Information, Control Number: **AFRL-PR-ED-TP-2002-008**
C.T. Brown & V.G. McDonell (Energy Research Consultants); Doug Talley, "Accounting for Laser
Extinction, Signal Attenuation, and Secondary Emission While Performing Optical Patterning in a
Single Plane"

15th Annual Conference on Liquid Atomization & Spray Systems
(Madison, WI, May 2002) **(Deadline: 15 Feb 2002)**

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Technical Advisor
Space and Missile Propulsion Division

Accounting for Laser Extinction, Signal Attenuation, and Secondary Emission While Performing Optical Patternation in a Single Plane

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Abstract

An optical patternation method is described where the effects of laser extinction and signal attenuation can be corrected for, and where secondary scattering effects are reduced by probing the spray with a swept beam instead of a laser sheet. The use of the swept beam also allows the signals to be detected within the same plane as the sweep, thus eliminating the requirement to perform a tedious 3D mapping in order to correct for signal attenuation effects. Conditions are described in which the method might possibly be applied to non-spherical droplets. Measurements in a fan spray indicate that the method is consistent with PDI measurements.

Introduction

Optical patternation is a technique whereby the spatial distribution of some spray property such as surface area or mass is sought over a plane by interrogating the spray using laser light, typically in the form of a planar sheet. The surface area distribution is typically sought using Mie scattering, while the mass distribution is typically sought using liquid-phase laser-induced fluorescence (LIF). When applied to dense sprays, quantitative interpretation of the resulting measurements can be subject to several sources of error. One source is reduction in incident laser light intensity due to the spray, referred to here as *laser extinction*. Another source of error is reduction in signal light (Mie scattering or LIF) by the spray, referred to here as *signal attenuation*. A third error source is multiple scattering, which can produce additional signals that cannot always be separated from the signals produced by the primary illumination. This third source will be referred to here as *secondary emission*.

Several groups have proposed optical patternator techniques that at least partially address the above errors. Sellens, *et al.* [1-3], used a Mie scattering technique where corrections are made for laser extinction but not for signal attenuation. Su, *et al.* [4], used a method similar to Sellens, *et al.*, to correct both Mie and LIF images for laser extinction. Talley, *et al.* [5-7], developed a method using counter-propagating sheets of laser light wherein corrections were made for both laser extinction and signal attenuation from LIF images alone, without requiring Mie images. Sankar, *et al.* [8], took the ratio of the LIF to Mie images to calculate the Sauter mean diameter, and argued that taking the ratio cancelled errors due to laser extinction and signal attenuation. Finally, Lim, *et al.* [9], used a six-axis instantaneous

tomographic technique based on laser extinction measurements where signal attenuation is not an issue. No group has thus far attempted to correct for secondary emission.

In what follows, a method is described in which laser extinction, signal attenuation, and secondary emission are all addressed, and which has other advantages described below. A discussion of when the method might be applied to non-spherical particles is also included.

Experimental Approach

The experimental approach may be described by first describing the approach to secondary emission. Unlike the approaches to laser extinction and signal attenuation to be described below, quantitative corrections to secondary emission are still not possible. Instead, secondary emission is minimized by isolating the incident light to a single beam of light that is scanned across the plane, instead of using a light sheet. This approach minimizes the total light power that interacts with the spray, thereby minimizing the opportunity for secondary emission. The impact of using a single beam of light is illustrated in Fig. 1. Figure 1a shows a non-corrected Mie scattering signal intensity profile across the diameter of a hollow cone spray that is illuminated by a laser sheet in the plane of the spray centerline axis. Despite the fact that almost no mass is present in the center of the spray, the measured intensity is non-zero due mainly to multiple scattering. In Fig. 1b, the sheet has been masked off to allow illumination only from a thin beam passing through the same diameter of the spray. The reduction in secondary scattering from other parts of the plane causes a significant reduction in the center intensity, without having to reduce the light power along the diameter being probed.

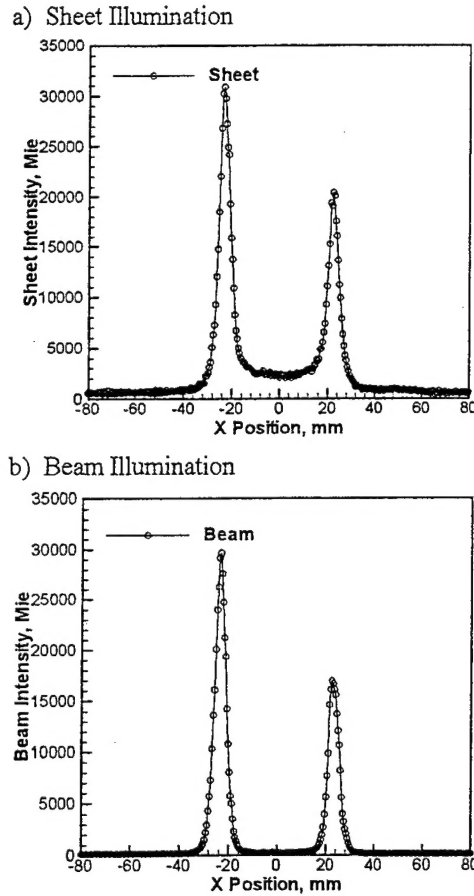


Figure 1. Line Profile of Measured Scattering from a Hollow Cone Spray.

The use of a single beam swept over a plane allows another important simplification. Figure 2a shows a typical optical patterning arrangement where the Mie or LIF signals are viewed by a 2D detector outside the plane of the laser sheet. Signals produced within the sheet must travel to the detector through parts of the spray that are not in the plane. If corrections for signal attenuation are to be attempted, then those parts of the spray outside the sheet through which the signals pass must also be measured, creating the requirement to perform a tedious 3D mapping (see Talley and Verdick [7]). With the swept beam approach, the detector can be moved into the same plane as the sweep, as illustrated in Fig. 2b, and all signals reaching the detector travel only through the plane. Thus full corrections can be applied without requiring a 3D mapping. Finally, moving the detector into the plane of the sweep offers the potential simplification of replacing the 2D detector with a 1D array, although this simplification was not evaluated in the present work.

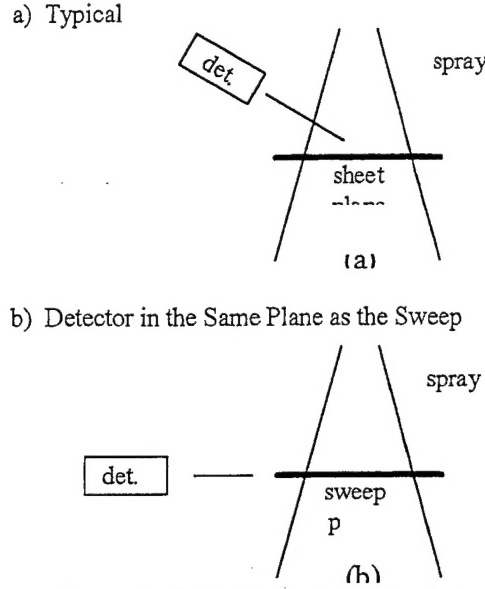


Figure 2. Optical Patterning Arrangements.

Analysis Approach

The time-averaged relationship between the laser energy and the detected signal energy is assumed to be of the form

$$E_n(x) = k_n e_b(x) e_c(x) \xi_n(x), \quad (1)$$

where x is the distance along the beam and k_n is a constant. The other terms in eq. (1) are defined as follows. The quantity E_n is the detected signal energy divided by the light energy entering the spray. The quantity e_b is a laser extinction coefficient, defined at each position x to be the ratio of the local laser energy to the initial laser energy entering the spray, $0 \leq e_b \leq 1$. The quantity e_c is a signal attenuation coefficient, defined at each position x to be the ratio of the signal energy at the detector to what the signal energy would have been in the absence of signal attenuation in the spray, $0 \leq e_c \leq 1$. The quantity ξ_n is a spectral band coefficient, where n is an index denoting the identity of the band coefficient. The two band coefficients which will be of concern here are the scattering band coefficient ξ_s in the case of Mie scattering, and the absorption or fluorescence band coefficient ξ_f in the case of LIF. The total extinction coefficient ξ will be the sum of the spectral band coefficients, which in the case of most sprays is expected to be dominated by the scattering coefficient. Thus

$$\xi = \sum \xi_n \approx \xi_s \quad (2)$$

The band coefficients are in turn assumed to be related to the spray properties of interest according to

$$\zeta_n = h_n \xi_n, \quad (3)$$

where h_n is another constant and ζ_n represents the spray property. In the case of Mie scattering, ζ_s will be the concentration of surface area, or surface area per unit volume. For spherical drops in a geometric optics regime, the constant h_s will be equal to 2, i.e., $\zeta_s = 2\xi_s$. In the case of LIF, ζ_f will be the concentration of droplet mass, or droplet mass per unit spray (gas + liquid) volume, where h_f will depend among other things on the concentration of the fluorescing molecules in the droplets.

According to Beer's law, the laser extinction coefficient obeys the relationship

$$\frac{de_b}{dx} = -e_b \xi \approx -e_b \xi_s = -\frac{1}{k_s} \frac{E_s(x)}{e_c(x)}, \quad \text{or}$$

$$1 - e_b(x) = \frac{1}{k_s} \int_{x_-}^x \frac{E_s(x)}{e_c(x)} dx, \quad (4)$$

where x_- is the point at which the laser beam enters the spray. Neglecting for the moment that $e_c(x)$ is not known, then since both $E_s(x)$ and the light energy exiting the spray are measured, the value of e_b is also known where the beam exits the spray, and eq. (4) can be used to calculate both k_s and the value of e_b at each point along the beam. Then the scattering coefficient ξ_s could be calculated using eq. (1). If $e_c(x) \equiv 1$ everywhere (no signal attenuation), then the analysis thus far is similar to that of Sellens, *et. al.* [1-3]. The procedure when $e_c(x)$ is not unity is described next.

If the scattering coefficient is isotropic, as would be a reasonable assumption in the average for most sprays, and if the scattering coefficient is the same for the signal as it is for the laser, then the signal attenuation coefficient will also obey a Beer's law relationship:

$$\frac{de_c}{ds} = -e_c \xi_s \quad \text{or}$$

$$e_c(x) = \exp \left[- \int_0^{s_d} \xi_s(s; x, \alpha_x, \alpha_y) ds \right], \quad (5)$$

where s is the distance along a path from point x to the detector, α_x and α_y are the direction cosines of the path, and where s_d is the distance to the detector. Equations (1)-(5) are then solved in "onion peeling" fashion as follows. Beginning with the Mie signals, no signal attenuation will be caused by the spray along the first row closest to the camera, so $e_c(x) \equiv 1$ along this first row. The scattering coefficient can therefore be calculated using eqs. (1)-(4). Along the second row, $e_c(x)$ will not be unity, but since the scattering coefficient is now known along the first row, $e_c(x)$ can be calculated for the second row using eq. (5),

and then the scattering coefficient can be calculated for the second row, and so on. Once the e_b and e_c fields are calculated, eq. (1) can then be used to calculate the fluorescence band coefficient to within the constant k_f . Note that it will not be possible to know the value of k_f without a separate calibration procedure.

It may be further noted that the scattering coefficient is calculated without having to relate scattering to droplet surface area or any other droplet property. In particular, *it is not necessary that the droplets be spherical* in order to measure the scattering coefficient. Corrections based on scattering can therefore also be applied to measure the fluorescence band coefficients, to within a constant, when the droplets are not spherical. The question of whether the fluorescence band coefficients are still proportional to the droplet mass when the droplets are not spherical would still remain.

Results

To evaluate the method, test data were obtained on a fan spray, as illustrated in Fig. 3. The concept of the fan spray was to provide a field which could be selectively oriented to produce either large attenuation of the incident light (the 0 deg orientation in Fig. 3), large attenuation of the signal light (the 90 deg. orientation), or little attenuation of either (the 45 deg. orientation). For the 0 degree orientation, data was obtained for light traversing from either direction.

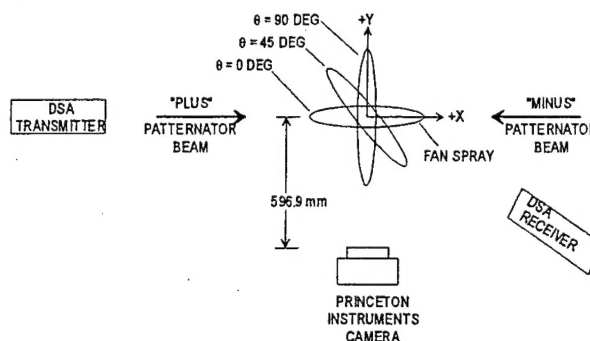


Figure 3. Fan spray configurations.

Water containing fluorescein dye at a molar concentration of approximately 10^{-6} was flowed through a Spraying Systems fan spray nozzle (SU13A-SS tip and 1/8 J-SS adapter) at a rate of 0.93 g/s. Nozzle air was injected at a flow rate of approximately 18,100 scc/min at 30 psig. Measurements were performed in an axial plane 35 mm downstream of the nozzle tip. An argon ion laser operating at 488 nm provided illumination, and the beam was imaged using a 16-bit ICCD Princeton Instruments camera. The beam and camera were fixed while the spray was traversed in 1 mm increments, and the camera imaged the beam through the plane of the traverse. Independent measurements of scattering and fluorescence were made by chang-

ing the filter in front of the camera. Nine images of the fluorescence and scattered light were averaged (each image had a 1.8 sec exposure) at each measuring location. Phase Doppler interferometry (PDI) was also applied in this plane, as is also indicated in Fig. 3.

Corrected and uncorrected line profiles of the LIF results across the major axis of the fan are plotted in Fig. 4. The 0 degree case where the beam propagates from the left is shown in Fig. 4a. The uncorrected intensity profile is skewed to the left due mostly to laser extinction. The corrected profile is more symmetric, as the actual spray is expected to be. The same comments apply to Fig. 4b, the 0-degree case where the beam propagates from the right, except that the skewness is to the right. The 45-degree case, where both laser extinction and signal attenuation should be at a minimum, is plotted in Fig. 4c. Both the corrected and uncorrected profiles are symmetrical, and the magnitude of the correction is indeed the smallest of all four cases. Finally, the 90-degree case is plotted in Fig. 4d. The uncorrected intensity profile is skewed to the side of the spray nearest the detector, due mostly to signal attenuation. The corrected profile is again more symmetric.

Since the mass concentration of the fan spray should be independent of the orientation, the corrected LIF profiles might be expected to also be independent of the orientation. However, Fig. 4 shows that the magnitudes of the profiles are somewhat different, which is attributed to several possible reasons. It is possible that the nozzle was slightly angled relative to the coordinate system associated with the traverse. It is also possible that the nozzle was not rotated about its exact centerline. These two possibilities are exacerbated by the steep gradients in the concentration near the centerline in both X and Y directions. For the 0 degree case, the plus and minus beams had slightly different diameters, although the power of the beams was maintained within 3%. Finally, the LIF corrections are capable of recovering the mass distribution only to within an undetermined constant, which could also explain the slightly different magnitudes.

To remove the effect of the undetermined constant, normalized corrected intensity profiles are plotted in Fig. 5, here interpreted as normalized volume concentration profiles (mass concentration profiles adjusted for a constant liquid phase density). The profiles are shown to roughly collapse upon each other, suggesting that, when the corrections for laser extinction and signal attenuation are applied, consistent results are obtained. Also plotted in Fig. 5 are corresponding PDI measurements, together with associated error bars. The optical patterning profiles are consistent with the PDI measurements.

Summary and Conclusions

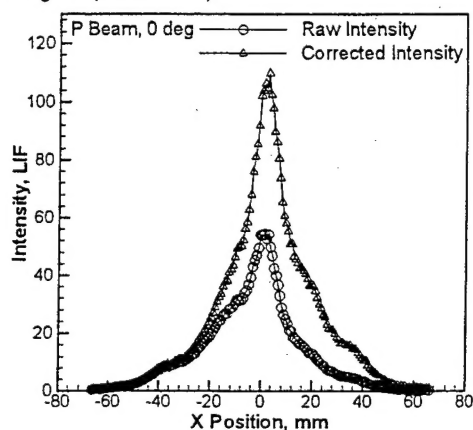
An optical patterning method has been developed which corrects for laser extinction and signal attenuation. Probing the spray with a swept beam instead of a laser sheet

minimizes secondary emission effects. The use of the swept beam also allows the detector to be moved into plane of interest, which (1) would not be possible with a sheet and (2) allows all corrections to be made within a single plane. Because the corrections only require the scattering band coefficient to be known, not the droplet surface area, the corrections can potentially be applied even when the droplets are non-spherical. Application of the method in a dense fan spray shows that the normalized volume concentration profiles are consistent with each other and with PDI measurements.

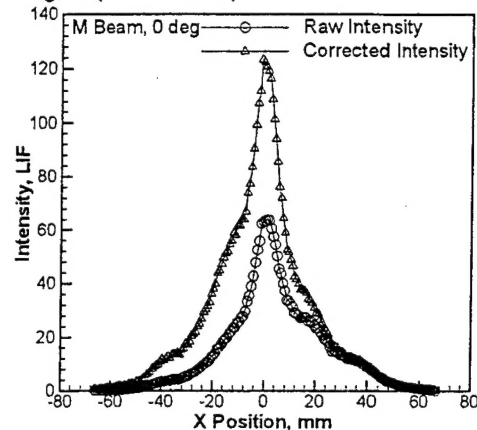
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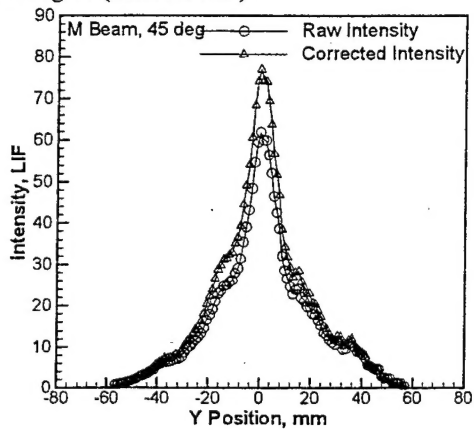
a) 0 degree (Plus Beam)



b) 0 degree (Minus Beam)



c) 45 degree (Minus Beam)



d) 90 degree (Minus Beam)

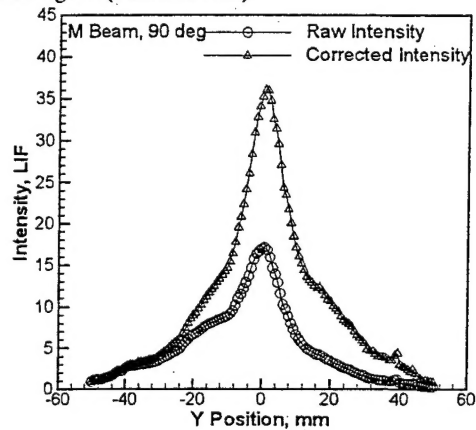


Figure 4. Line profiles.

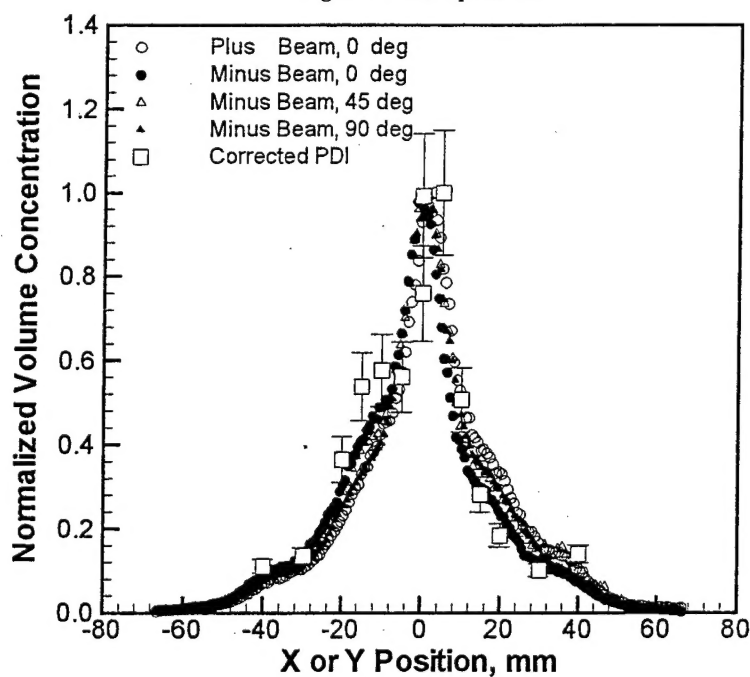


Figure 5. Normalized profiles.